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(54) Self-focusing antenna array

(57) A phased array of antennas (11-14) for transmitting electromagnetic power to a target 2, e.g. a microwave powered aircraft, is focussed and steered by feedback from the target 2. Each antenna (11-14) of the array is phase modulated in turn, and the resulting amplitude modulation of the combined field at the target 2 is used to calculate a correction to the specific antenna phase, which is telemetered back to the array system and applied to the antenna phase shifter, in order to maximise the ratio of the combined field at the target.

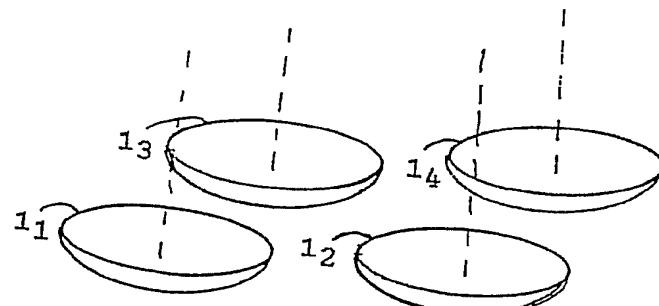
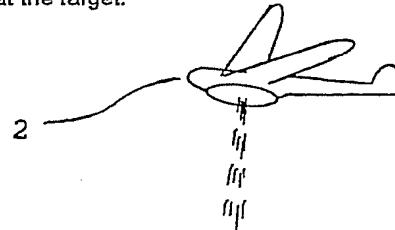


FIG 1.

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

This print takes account of replacement documents submitted after the date of filing to enable the application to comply with the formal requirements of the Patents Rules 1990.

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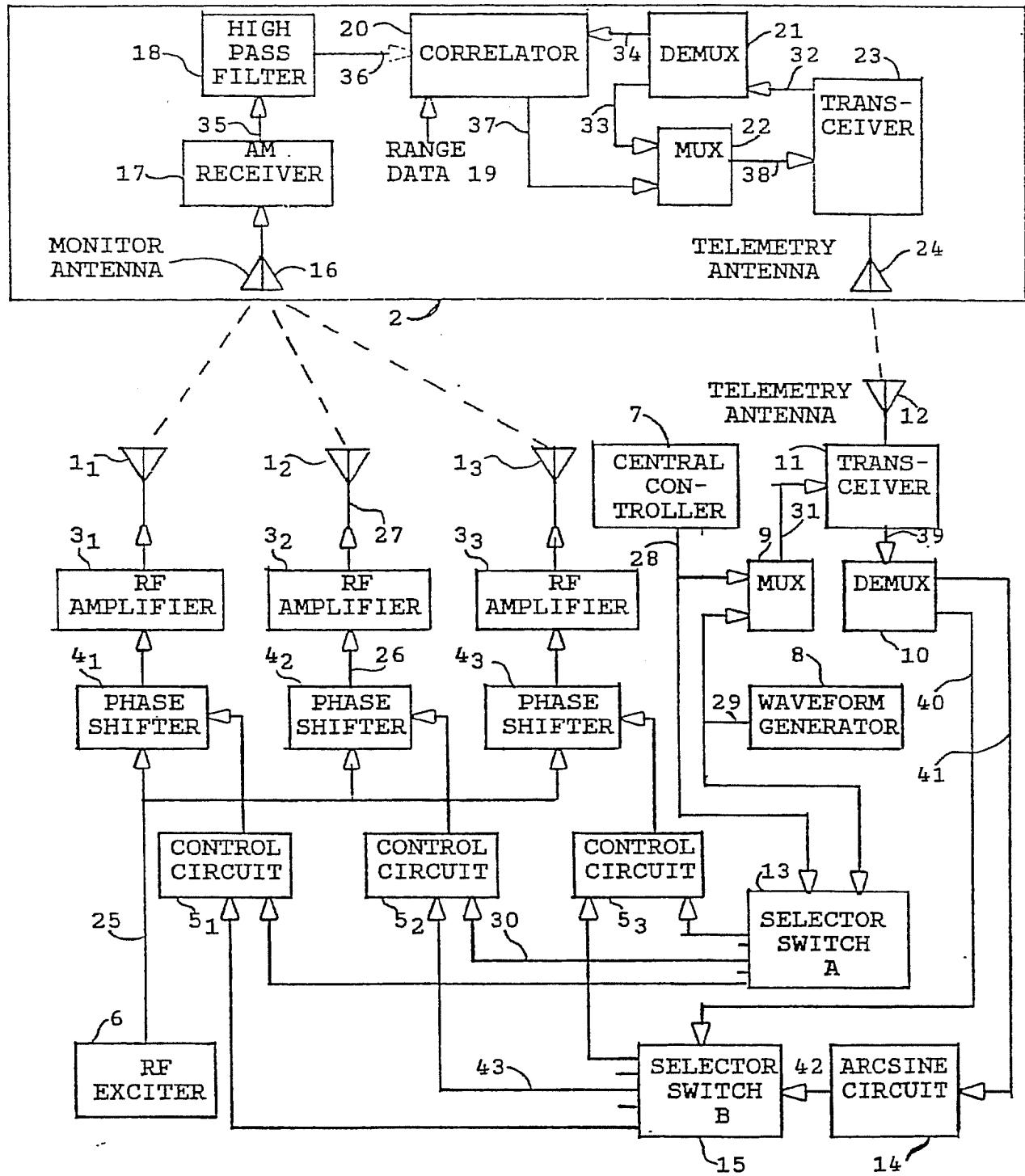


FIG. 2

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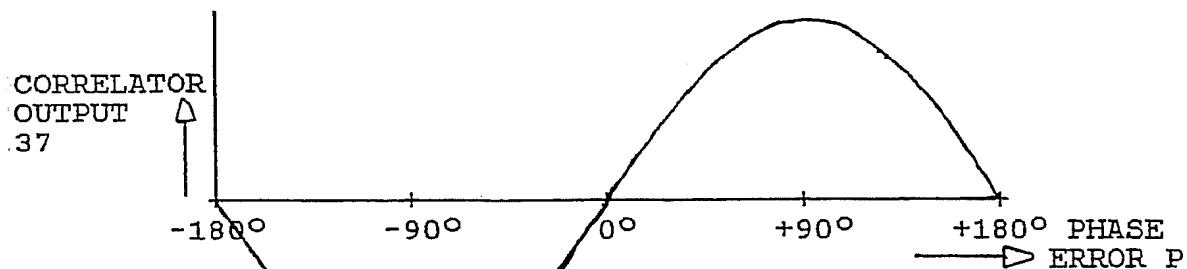


FIG. 4

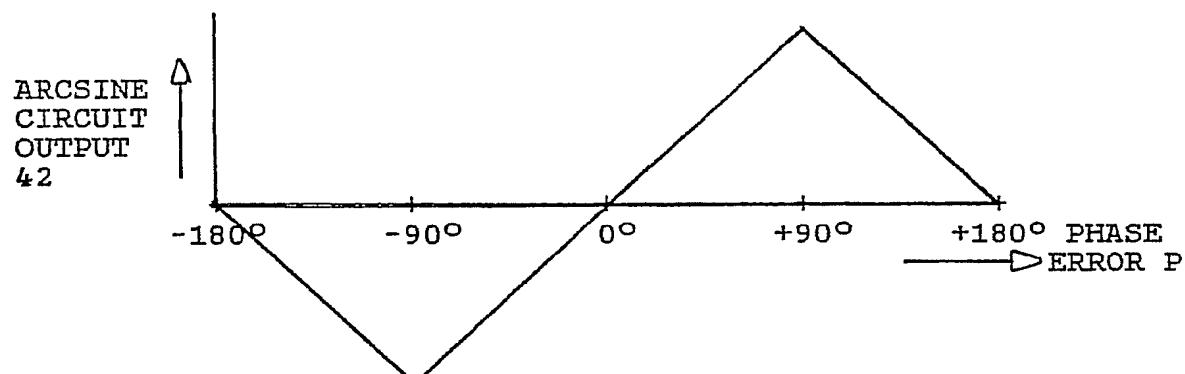


FIG. 5

signals from the radiators all arrive at the target substantially in phase with each other.

In the description which follows, an antenna is an individual radiator or a group of radiators, in either case controlled by a single phase shifter.

The Problem.

The problem is to adjust all the phase shifters in an array of antennas continually to keep the beam pointing at, and focussed on, the target. The Prior Art for doing this includes the conventional method; the retrodirective array; and the adaptive array.

Conventional Phased Array Technique.

The conventional approach is to feed the antennas from a common source of carrier frequency power (the RF exciter) through equivalent cable lengths to form a boresight beam, then apply calculated phase shifts to allow for the off-boresight angle of the target. To achieve the boresight beam may require an extensive calibration procedure, which must be repeated periodically to correct for temperature and other disturbing effects. To aim the beam at the target requires a calculation of phase shift for each element, to be repeated as the target moves. Such a system is described in U.S. Patent no. 4,445,119 by G.A. Works and assigned to Raytheon Company.

It should be noted that a parallel beam is not the optimum: for maximum efficiency the beam must converge on the target to an extent which depends on the distance of the

contained in a paper by Attia and B.D. Steinberg in the January 1989 issue of the Transactions of the Antennas and Propagation Society of the IEEE (Trans A & P). B.D. Steinberg describes adjustments to the phases in the elements of a radio camera in the January 1978 issue of Trans A & P. P.V. Brennan describes a self-phased array in the July 1989 issue of Trans A & P.

Adaptive array.

The concept of monitoring the signal radiated by a large antenna is described in U.S. Patent no. 4,163,235 by J.L. Schultz and assigned to Grumman Aerospace Corporation. An array of lasers (not antennas) which is adaptively phased is described in U.S. Patent no. 3,731,103 by T.R. O'Meara and assigned to Hughes Aircraft Company: the phases of all laser outputs are simultaneously modulated sinusoidally each at a unique frequency, and the resultant amplitude modulation of the combined field at the target is analysed back at the laser location to optimise the phases.

SUMMARY OF THE INVENTION

The problem.

A microwave powered airborne vehicle obtains its power for sustaining flight by microwave power transmitted from a large antenna array on the ground, containing many phase shifters. In order to maximise the efficiency of power transfer to the target vehicle, these phase shifters must be controlled in such a way as to form, steer and focus the beam from the array on to power collecting antenna on the

sine function, and the phases of the antennas are continuously updated by tracking circuits.

An object of the invention is to simplify the system by using a single channel for the entire array for detecting required adjustments to each antenna instead of a receiving channel for each antenna. A further object of the invention is to adapt the array as rapidly as possible by making the corrections from each test as complete as possible, and by using tracking circuits to maintain correct phases even between tests.

Further advantages of my invention will become apparent in the following description.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an elevation view of the ground antenna array and the target vehicle;

FIG. 2 shows, in schematic form, the main electrical components of the proposed system arranged in accordance with this invention;

FIG. 3 shows, in a phasor diagram, the phase relationships between fields at the target;

FIG. 4 shows the relationship between the signal sent down through the telemetry channel and the phase error P;

FIG. 5 shows the relationship between the phase correction applied to the selected phase shifter and the phase error P.

grouped together. Each antenna 1 has associated with it a radio frequency amplifier 3, a phase shifter 4 and a control circuit 5. Each control circuit 5 has a unique address and contains an accumulator whose contents can be increased or decreased by inputting a positive or a negative number. The contents of the accumulator produce a substantially linear change in the phase delay through the associated phase shifter 4, with a scaling factor such that when the accumulator changes from full to empty the phase delay changes by substantially 360°. The contents of the accumulator can also be changed in synchronism with an applied modulating waveform so that the phase delay through the phase shifter is increased and decreased by 90°.

In FIG.2, radio frequency exciter 6 supplies power 25 at the desired carrier frequency to the phase shifters 4, each of which according to the state of its associated control circuit 5 controls the phase of the carrier power 26. The carrier power 26 goes to an associated radio frequency amplifier 3 which amplifies the power to the desired level and sends such amplified power 27 to its associated antenna 1. Central controller 7 sends address 28 to first multiplexer 9 and also to first selector switch 13 to select the control circuit 5 which has that address. Waveform generator 8 sends a modulation waveform 29 to first multiplexer 9 and also through selector switch 13 to the selected control circuit 5 which by means of associated phase shifter 4 causes the phase of the signal radiated by

error signal 41 from the received signal. Arcsine circuit 14 accepts error signal 41, modifies it to 42 and passes signal 42 to second selector switch 15. Address 38 (doubly delayed from address 28 by time of flight to target and back) causes second selector switch 15 to select the same control circuit 5 which was selected previously by first selector switch 13. The output 42 of arcsine circuit 14 is sent by second selector switch 15 to the selected control circuit 5 to correct the phase of the signal radiated by the associated antenna.

The means by which my invention adjusts and optimises the phase of every antenna 1 in the array is as follows. In FIG.3,

44 = field from antenna 1n, unmodulated condition

44' = field from antenna 1n, phase advanced 90°

44" = field from antenna 1n, phase retarded 90°

45 = combined field from all antennas 1 except 1n

45' = combined field from all antennas with 1n phase advanced

45" = combined field from all antennas with 1n phase retarded

If fields 44 and 45 are not in phase, then the selected antenna 1n is not making the maximum possible contribution to the field at the target 2: the phase difference between fields 44 and 45 is known as the "phase error" P of the selected antenna. When the phase shifter 4 associated with the selected antenna 1n is being modulated, the field

further delayed by time of flight from target to transmitting location. Demultiplexer 10 separates output 39 into the address 40 which is passed to second selector switch 15 which selects the control circuit which has that address, and error signal 41 which is essentially  $\sin P$  and is fed to the arcsine circuit 14. The output 42 of arcsine circuit 14 goes through second selector switch 15 to the selected control circuit 5 and causes the unmodulated phase of associated phase shifter 4 to be changed accordingly.

Referring to FIG.4, the output 37 of correlator 20 is plotted against phase error  $P$ , and is a sine function of phase error  $P$ . In FIG.5, the output 42 of the arcsine circuit 14 is plotted against phase error  $P$ , and is a linear discontinuous function. If the phase error  $P$  was between  $-90^\circ$  and  $+90^\circ$ , the output 42 of arcsine circuit 14 essentially completely removes the error  $P$  in the radiated signal. If the original error was between  $-180^\circ$  and  $-90^\circ$  or between  $+90^\circ$  and  $+180^\circ$ , the error  $P$  is partially removed: after one or more repetitions of the process, the error is essentially completely removed.

Central controller 7 selects each control circuit 5 and its associated phase shifter 4 and antenna 3 in turn. When it has selected all of them, it repeats the process continually. Thus as the target vehicle moves, the array of antennas is continually adapted to maximise the field at the vehicle 2.

frequency: in order to minimise the effects of accidental or deliberate interference, it is a random or pseudo-random waveform. The average frequency of waveform 29 is in the order of 1 MHz, depending on the number of antennas 1 in the array and the speed of the target 2. The output 36 of the high pass filter 18 is also a square wave essentially synchronous with delayed waveform 34. The amplitude of signal 36 is proportional to  $\sin P$  and inversely proportional to range, and therefore the product of signals 34 and 36 is also. This product is converted to digital form by an analog-to-digital converter in correlator 20: range data 19 is also digital and a digital multiplier in correlator 20 produces output 37 (which is essentially  $\sin P$ ) in digital form. Arcsine circuit 14 contains a "look-up" table and its input 41 and output 42 are both digital. Address 28 and all quantities in control circuits 5 are in digital form. The two multiplexers 9 and 22 use frequency division to combine their inputs. However there are many other possible configurations: for example, some analog quantities could be digital, or some digital quantities could be analog.

increase the contribution of said selected antenna to said combined field at said target

(g) a telemetry transmitter and telemetry antenna at said target and a telemetry antenna and telemetry receiver at said transmitting location

all said means combining to form a closed feedback loop which maximises the ratio of said combined field at said target to said transmitted electromagnetic power.

2. A system as in claim 1, in which said target is an airborne or spaceborne vehicle.

3. A system as in claim 2, in which said detection means is located at said target.

4. A system as in claim 3, in which

(a) a second telemetry transmitter is located at said transmitting location

(b) a second telemetry receiver and said correlation means are located at said target

(c) said second telemetry transmitter and said second telemetry receiver convey said waveform from said waveform generating means to said correlation means

(d) said first telemetry transmitter and said first telemetry antenna convey said correction signal from said correlation means to said transmitting location.

5. A system as in claim 4 in which the address of said selected antenna is conveyed from said transmitting location to said target and back to said transmitting location by said telemetry transmitters, receivers and antennas.

antenna is phase modulated so that the antennas need to be phase modulated less frequently.

13. In a system for supplying power to an airborne or spaceborne target by radiation of microwave power from the ground,

- (a) a plurality of antennas each having a unique address
- (b) an exciter generating radio frequency power which is distributed to said antennas
- (c) for each said antenna, means to amplify said power from said exciter and to apply it to said antenna, means for shifting the phase of said radio frequency power radiated by said antenna and controlling means for controlling said phase shifting means, said controlling means causing said phase shift to remain constant at a usual value except when it is selected to be phase modulated about said usual value and except when it is selected to have said phase shift corrected
- (d) timing means to select the address of each said antenna in turn
- (e) means for generating a pseudo-random alternating waveform
- (f) first means for selecting in accordance with the address selected by said timing means any one of said antennas and causing its said phase controlling means to phase modulate it away from

(1) second selecting means for selecting said antenna specified by said address received from said target and applying the output of said inverse sine calculating means to said phase controlling means of said selected antenna to increase or decrease said usual phase shift in order to maximise the contribution of said selected antenna to said combined field at said target all said means combining to form a closed feedback loop which maximises the ratio of said combined field at said target to the total amount of said radiated power.

Category	Identity of document and relevant passages	Relevant to claim(s)

#### Categories of documents

X: Document indicating lack of novelty or of inventive step.

Y: Document indicating lack of inventive step if combined with one or more other documents of the same category.

A: Document indicating technological background and/or state of the art.

P: Document published on or after the declared priority date but before the filing date of the present application.

E: Patent document published on or after, but with priority date earlier than, the filing date of the present application.

&: Member of the same patent family, corresponding document.

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